Most meticulous surveys have been made of some of the larger glaciers, and by means of tunnels, sponsored by hydroelectric concerns, much is being learned about internal structure of ice masses.

The polar explorer and scientist is intimately interested in the climate both present and past. The study of glaciers is one of the most valuable in the elucidation of climatic history. As we move back in time, glacial geology takes over from pure glaciology as the science concerned with collecting the evidence. We are back to the geologist again. But the fields of meteorology, physics, and botany have been drawn in, and the practical work of the engineer is required to assist the field investigator, who must still have a strong back and a love for snow and ice.

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Some Aspects of Glaciological Research. By Robert P. Sharp[1]

The following brief comments make no pretence at providing a complete survey of desirable research in glaciology. The aim is rather to "sign post" the beginnings of trails that might be followed by interested workers. These investigators must themselves become well informed on the basic principles, so they can independently evaluate the desirability of a specific program and determine the best means of carrying it forth. No one can or should try to tell someone else how to tackle a research problem. They can only indicate some of the areas that appear worthy of consideration, and that is the objective here.

Velocity relations in glaciers

Differential movements within glaciers, both in time and space, have been recorded for more than a century (Forbes, 1843, pp. 124–56). In view of this

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extended observation and the data obtained (Hess, 1904, pp. 115–50; Klebelsberg, 1948, pp. 80–9), it is truly surprising that so much remains to be done. Large, relatively untouched but highly promising areas of investigation in the field of velocity relations invite attack. For ease of discussion, differences in surface velocities are treated, first with respect to spatial relations and then with respect to temporal variations. This is followed by consideration of velocities at depth in glaciers.

Surface velocities: Many studies on different valley glaciers provide a reasonably good picture of velocity distribution along transverse profiles on the surface. More efforts should be directed toward obtaining data on velocities over the entire surface of the glacier, as only a little information of this type is available (Hess, 1904, p. 136). This will have to be done by means of carefully controlled measurements at a network of widely distributed points and not just along two or three profile lines. At the same time information should be obtained that will allow an evaluation of the influence on flow velocity of surface slope and channel characteristics, especially width and depth.

If velocity studies are possible only along profile lines, efforts should be focused on longitudinal profiles. Such data are of prime importance as a means of testing theoretical concepts bearing on extending and compressive flow in glaciers (Nye, 1952, p. 89). Little information is available on longitudinal velocity changes in North American glaciers (Matthes, 1946, pp. 222–5; Matthes and Phillip, 1943, p. 21). The situation is better for European glaciers (Hess, 1904, pp. 128–35, 148; 1933, pp. 37–8), but quantitative data are needed.

Nearly all measurements of surface velocity to date have recorded only the downvalley component parallel to the glacier surface. It has long been recognized that the absolute direction of movement is actually oblique to the surface and of different angles and different amounts from place to place (Hess, 1933, p. 41). The failure to build upon Reid's (1896, pp. 917–21; 1901, pp. 749–50) early work on this matter is a striking oversight, and this remains a promising and fertile line of investigation.

Variations of flow velocity in time constitute a closely allied subject for study. Although more and better quantitative data on seasonal velocity fluctuations would be useful, measurements over shorter periods provide an even more fruitful line of investigation. Such measurements must be carefully controlled or the data will be open to such question and uncertainty as to make them almost worthless. Some earlier investigations of short-period variations have not been rigorously controlled, and most, if not all, have been made with respect to a single station on the glacier surface. Indications are that the care and labour required to make reliable short-period measurements at a number of stations will be well worth the trouble. Preliminary studies on the Saskatchewan Glacier (Meier *et al.*, 1954, pp. 9–12), show that surprising and puzzling differences of velocity occur from day to day between stations located in the same flow-line as well as beween stations in different flow-lines. Adjacent flow-lines are not always coordinated in their periods of acceleration or deceleration, and different parts of the same flow-line behave differently during the same interval. It seems that much can be learned about the nature of glacier movement from short-period observations of a number of points on the glacier surface.

Instances of exceptional acceleration and deceleration show a definite but unexplained correlation with major meteorological events, especially periods of precipitation. Much more field data on this type of relation must be gathered before even the crudest type of analysis from the standpoint of physical mechanics will be possible. Whether the erratic velocity behaviours involve some sort of wave movement within the ice, or whether the normal processes of flow respond directly and sensitively to variations in the meteorological elements cannot be determined on the basis of present information.

The movement of waves or surges through a glacier needs more study. Such surges have been recognized (Hess, 1931, p. 240, 1933, pp. 94–5; Finsterwalder, 1937, p. 99; Streiff-Becker, 1938, pp. 18–19; Klebelsberg, 1948, pp. 87–8), and one is currently progressing down the Nisqually Glacier on Mount Rainier in Washington (Harrison, 1951, p. 11). It is of utmost importance that these phenomena be carefully observed and their various behaviours recorded. An understanding of the mechanics involved would certainly further our knowledge of glacier flow. In addition, they are obviously important in causing erratic advances at the terminus of a glacier.

Glaciology, like many other phases of earth sciences, is currently passing from a stage of general observation to one of more careful quantitative measurement. The temporal and spatial differences of velocities in glaciers are good subjects for this type of study.

Velocity relations at depth: Little is known about the distribution of velocity with depth in glaciers, although such information is even more essential to an understanding of glacier flow than surface data. Considerable information on stress–strain conditions at depth, and on the physical properties and behaviour of ice under confining pressures, as they occur under natural conditions, can be gained from the vertical velocity profile in a glacier.

Data on velocities at depth are scant because they are difficult to obtain, but their value justifies the effort. A bare beginning has been made, and more data should be gathered from ice streams on slopes and ice sheets on flats. Those interested in this type of investigation can learn of procedures previously used from the following references: Gerrard, Perutz, and Roch (1952) and Sharp (1953).

Structures in glaciers

Glaciology offers many problems for study, but if an attempt were made to select a few of basic importance, the subject of glacier flow would certainly be among them. Attacks on this problem can be made from various directions and should include both field and laboratory investigations. One avenue of field approach is through study of structures within glaciers. Since most of these structures have been created by or because of flowage, knowledge of them and their origin is bound to promote understanding of the mode and mechanism of glacier flow.

Planar structures: Crevasses and faults are surface features, to be sure, but they are the product of stresses generated in the crustal ice by movements deeper within the glacier. Field studies of crevasses have not kept pace with theoretical analyses of the stresses leading to their formation (Lagally, 1929; Nye, 1952, pp. 89–91). Brief field inspection shows that crevasses are more varied and complex than might be supposed. Many different types can be recognized, and each type must have a particular meaning with respect to stress conditions in the glacier. Crevasses need the attention of someone well versed in solid state physics and engineering principles dealing with stress, strain, and the behaviour of brittle materials. Faults should also be studied, for they are just as significant, and perhaps easier to interpret.

A thorough investigation of foliation in glacier ice would likewise be desirable. A satisfactory explanation of its origin, and an understanding of the attitude and structure of foliation planes in various parts of the glacier are lacking. Most investigators regard foliation as a secondary structure imposed on the ice by flowage, but a few look upon it as wholly or in part a relic of sedimentary layering inherited from the firn. However, even among those regarding foliation as secondary, the mode of origin is a subject of some debate. This is a matter intimately related to the mechanics of glacier flow, and an understanding of either is likely to be promoted by advances in the other. A satisfactory explanation is also lacking for the fact that the spoon-shaped structure of foliation planes, observed near the terminus of a simple valley glacier, does not extend any distance up the glacier, at least on the surface.

In recent years geologists have made considerable progress in understanding the form and emplacement of relatively homogeneous igneous bodies through careful mapping of all structures displayed therein. Similar investigations of glaciers might prove fruitful if all crevasses, faults, foliation planes, debris layers, sedimentary structures, lineation (if any can be recognized) and related features were mapped. This would be difficult to do because structures in glaciers are usually so profuse and locally so complex that detailed mapping leads more to frustration and confusion than to clarification and understanding. Anyone undertaking such a study should select the smallest, simplest glacier available as an initial subject.

Rhythmic banding (ogives) in steep valley glaciers deserves further investigation because it in turn can lead to an understanding of the mechanics and behaviour of these ice streams (Leighton, 1951). The interrelation of individual ice streams in compound valley glaciers, and the origin of the complexly deformed debris layers displayed by many ice masses present unsolved problems worthy of study.

Crystal fabrics: Investigations of crystal fabrics in glaciers are undergoing the same history as the earlier studies of fabrics in rocks. Strong orientation patterns have been demonstrated, but no satisfactory explanation for them has yet been evolved. This comes about in large part because knowledge of the behaviour of polycrystalline aggregates of ice under stress is so incomplete. Laboratory investigations are clearly called for, and a beginning is being made in this direction, particularly by J. W. Glen in England, and by D. T. Griggs and G. P. Rigsby in the United States.

It is entirely possible that the strong crystallographic orientations demonstrated in ice at the glacier's surface (Rigsby, 1951, 1953) are the product of an ordered recrystallization proceeding from an orientation earlier established by flowage at depth. A study of ice samples obtained from considerable depth by coring would be helpful in evaluating this hypothesis, if the relaxation rate is not too rapid and if the specimen is not too greatly disturbed by the coring procedure. Core drilling in glaciers has so far been too shallow for such purposes (Miller, 1953, p. 14), but this matter should be pursued further.

Much remains to be done with field studies of crystal fabrics, and a recent suggestion that shear planes of several different orientations in the glacier are involved merits further investigation (Schwarzacher and Untersteiner, 1953, pp. 121–4). However, the greater need at the moment is for controlled laboratory experimentation to establish the principles by which preferred orientations are developed in aggregates of ice crystals.

Phase relations in glacier ice

In 1950 H. Bader made an exploratory study of relations between the liquid, vapour, and solid phases of water in glaciers with respect to the conditions of temperature and pressure to which the ice had been subjected. This work was largely preliminary in nature, and the results obtained were different from those expected. Nonetheless, it appears that much can be learned concerning the properties and behaviour of ice at depth within a glacier from investigations of phase relations. Some of this work can best be done in the field, as the laboratory cannot reproduce wholly satisfactorily the conditions to which the ice in glaciers is subjected.

Oxygen-isotope studies in snow, firn, and glacier ice

Pioneer investigations of oxygen-isotope ratios ($0^{18}/0^{16}$) in waters of various origins reveal that water in glaciers is exceptionally light, that is low in 0^{18} (Epstein and Mayeda, 1953). Furthermore, preliminary studies show sizeable differences in the $0^{18}/0^{16}$ ratio within a single glacier. Data are still too scanty to demonstrate any consistent trends in the oxygen-isotope ratios in glaciers or to relate them to other factors, but these differences may well reflect environmental conditions at the point of origin of the ice, or they may be influenced by something within the subsequent history of the ice such as age, amount of flow and recrystallization, and temperature regime. This type of investigation is in its earliest stages, but it looks promising. Close coöperation between the geochemist and the field glaciologist will be required to produce results.

Micrometeorology and the regime of glaciers

Micrometeorology has been studied for some time with vigour and profit in Scandinavian areas (Wallén, 1948), but it has been largely neglected in North America, save for some work currently underway (Hubley, 1953). Glaciers are frequently referred to as "historians of weather", but weather records from glaciers cannot be interpreted without an understanding of how they respond to the various meteorological factors. Furthermore, the relative influence of the several meteorological elements involved displays such gross variation, depending upon environment, that detailed studies on many different glaciers in many different areas will be required before an evaluation of the basic relations will be possible.

A means of checking the reliability of micrometeorological studies is available if a correspondingly accurate determination of the ablation of firn and snow can be made. Measurements of ablation to date have been too crude and inaccurate to provide reliable values for balancing the ablation equation. It is not feasible to go into details here concerning the difficulty of making an accurate measure of ablation in firn or snow (Hubley, 1953, p. 18). It is a difficult matter, but one well worth considerable study and effort.

Micrometeorological studies on glaciers have significance outside the field of glaciology. The proper evaluation and understanding of climatic changes recorded by present and past glacier behaviours have a bearing on all activities of mankind affected by the climatic environment. The science of meteorology should also benefit, as a glacier surface furnishes an ideal subject for studies of heat exchange at the earth's surface.

Closely allied with the subject of glacier response to climatic change is the synchronism or non-synchronism of glacier behaviours in widely separated regions. When one deals with ancient fluctuations of glaciers the techniques of glacial stratigraphy and geobotany come into play, but even these ancient fluctuations should be interpreted on the basis of sound glaciological and micrometeorological principles. Eventually, Carbon-14 dating may be helpful in establishing the more ancient relations, provided the method can be properly refined and applied to the problem. A demonstration of closely synchronous glaciations in opposite hemispheres, with some degree of antiquity, would have major significance with respect to theories bearing on causes of glaciation.

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